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Experimental and theoretical analysis of the stress–strain state of anisotropic multilayer composite panels for wind turbine blade

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A B S T R A C T

Wind turbine blade is made of multilayer composite materials, which is exposed to various temperature changing environmental conditions like snowing, icing, and heating from visible and ultraviolet ray. This can make stress and strain for all life time continuously. Therefore the stress–strain state of anisotropic multilayer composite panels (plates) was analyzed with temperature loadings in this study. Experimental investigations and theoretical calculations were carried out for square carbon plastic composite panels with dimensions of 300 × 300 mm. Panels were manufactured at the curing temperature of about 175 °C, and were cooled to room temperature of about 23 °C. The method of analysis of the stress–strain state of multilayer composite panels was developed for determining functional suitability of composite structures. Mathematical model of this method is based on the classical theory by applying the Kirchhoff hypotheses and Cauchy equations and allows to investigate the stress–strain state of the composite material for establishment of standard high-precision structure surfaces under conditions of technological and temperature loadings. Peculiar composite properties, for example, anisotropy of thermo-mechanical properties, were taken into account for analysis of the stress–strain state of multilayer composite panels. The FORTRAN – software for parametric analysis of the stress–strain state of composite structures was developed on the basis of this mathematical model. Practical recommendations were given for designing of composite structures. Comparison of calculated results with experimental data of hogging (deflection in z-axis direction) for center points of composite panels shows the correctness of the mathematical model and method of the analysis by virtue of the fact that the divergence of results varies from −7.5% to 16%.

1. Introduction

Composite materials hold special place in various industries in the past few decades. They are widely used in the manufacture along with more traditional materials with a “monolithic” structure, such as metals, plastics and other, the reason is that the special properties of composites such as high specific stiffness, acoustic and thermal insulation properties, damping and vibration absorbing characteristics and etc. These immense advantages allowed to the composites take a leading position in the manufacture of wind turbine blade including aerospace engineering, building, shipbuilding, chemical industry and other areas. Being aware of the very responsible composite's role, the development of efficient methods for calculating the layered anisotropic plates and shells are the most urgent task for today's scientists and researchers. Principles of calculation and design of composite structures, the possibility of using advanced composite materials in various types of structures was discussed in various reviews, monographs, and papers.

Remain thermal stress of the composite materials from the cooling process of manufacturing can make lower the level of threshold stress or fracture stress which is manly occurred in the operating of wind turbine. Therefore the wind turbine blade can be destroyed even in the very lower operating load than the design limitation. Also, it can be the reason for deflections like hogging and sagging due to the thermal load. For obtaining of the perfect and precise surface during of manufacturing process of wind turbine blade avoidance of the thermal load is needed. So, main purpose of our paper is to develop the analysis method for the thermal stress and strain in the composite manufacturing process, and verify with experimental data. The maximum possible temperature of 175 °C is

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Nomenclature

B	thermo-elastic characteristics of the fiber
E	modulus of elasticity
$E_1^{(K)}$	modulus of elasticity in the longitudinal direction of the layer
$E_2^{(K)}$	modulus of elasticity in the perpendicular direction to the fiber direction
$G_{12}^{(K)}$	shear modulus
K_{HB}	nondimensional coefficient of the determining of the fiber tension level, varied (modulo) from 0 to 1
K_i°	the curvature of the panel
Ku	coefficient of signal amplification
L	mirror diameter
M	thermo-elastic characteristics of the matrix
M_I^T	thermal moments
M_I^H	tension moments
$m^{(K)}$	trigonometric function of the rotation angle of the coordinate axes of the K-th layer relative to the Cartesian coordinate system (x, y) if there between is the contiguous side
$n^{(K)}$	trigonometric function of the rotation angle of the coordinate axes of the K-th layer relative to the Cartesian coordinate system (x, y) if there between is the opposed side
N_I^T	thermal forces
N_I^H	tension forces
$Q_{IJ}^{(K)}$	layer stiffness for unidirectional fiber-reinforced plastic in elastic symmetry axes
$\overline{Q}_{IJ}^{(K)}$	layer stiffness reduced to an arbitrary x and y axes of the Cartesian coordinate system
T	temperature
ΔT	differential temperatures (between curing temperature and room temperature)
$U0\ (x, y, z)$	displacement of the reference plane, if $z = 0$
V	volume content of the fiber and the matrix
$V0\ (x, y, z)$	displacement of the reference plane, if $z = 0$
W	hogging of the composite panel
Z; z	Z-coordinate
$\alpha_1^{(K)}$	linear expansion coefficient in the reinforcement direction
$\alpha_2^{(K)}$	linear expansion coefficient perpendicular to the reinforcement direction
$\gamma_{x,y}^{\circ}$	deformation in the reference plane (tangent)
$\overline{\varepsilon}_B^{(K)}$	admissible deformation of the K-th composite layer
$\varepsilon_x^{\circ}, \varepsilon_y^{\circ}$	deformation in the reference plane
λ	wavelength of the electromagnetic emission
$\nu_{12}^{(K)}$	Poisson's ratios in the reinforcement direction and perpendicular to it, respectively
$\nu_{21}^{(K)}$	Poisson's ratios perpendicular to the reinforcement direction
$\overline{\sigma}_c^{(K)}$	admissible compression stresses
$\overline{\sigma}_p^{(K)}$	admissible tension stresses
$\overline{\tau}_{12}^{(K)}$	admissible stresses (tangent).

selected for the verifying our analysis scheme because of already taken data in the industry laboratory. For wind turbine blade materials, the maximum carbon content can reach to 40%, or more by weight for the huge size of wind turbine blade over 7 MW, and the maximum curing temperature can be used in manufacturing process. The analysis results with the temperature of 175 °C in this study can be expanded to the cases of lower curing temperature and different percentage of carbon in materials shortly hereafter. Our recommendations and identified trends can be applicable to a wide class of wind turbine blade materials.

Thermal stresses in multilayered plates were taken into account with shear deformation and anisotropy [1,2] and were researched for stress–strain state of composite materials in the eighties of the last century. Effect of the number of layers and the type of their laying for the stress–strain state of laminated composite plates and shells under the influence of external and residual stress with using the theory of thin multilayered plates was first considered by Tsai [3]. Residual stresses in layered composites were investigated by Chamis [4]. Later was studied of residual stresses in the Super Hybrid Composite [5]. In the all previous scientific papers, authors used well known classical equations of the composite materials theory for the calculation of strain–stress of composite materials, and among other things, separate equations for different composite structures characteristics (temperature, power, manufacturing errors and etc.) were obtained for the case of composite plates having the symmetric boundary data. As opposed to other investigations, this paper studies method of calculation of the stress–strain state of the anisotropic multilayer composite panel with taken into account asymmetric structure of the composite material, different boundary data, technological residual stresses and tolerances of the laying fiber, and temperature and power loads simultaneously. Mathematical model of this method is based on the classical theory of thin multilayered plates due to simplicity and rapid implementation of the calculations. Comparison of experimental and theoretical data for hogging shows close values. As a result, it is concluded that the proposed method for calculating of the stress–strain state of the layered anisotropic plates is valid and can be used in real manufacturing process.

2. The mathematical model of the stress–strain state of the multilayer composite structure with account for operational and technological influences

One of the main problems of high-precision structure is providing the minimum deviation from the profiled edge of the theoretical contour defined by a function $y = f(x)$ under operation conditions and under temperature influence. The program was developed for determining functional suitability of composite structures. The given program is based on the classical theory by applying the Kirchhoff hypotheses and Cauchy equations, and allows investigating the stress–strain state of the composite material for establishment of standard high-precision structure surfaces under conditions of mechanical and temperature loadings. Peculiar composite properties, for example, anisotropy of thermomechanical properties, shall be taken into account for stress–strain state analysis of the anisotropic multilayer composite panels.

Table 1
Carbon plastic properties.

Properties	Elastic modulus, E, GPa	Shear modulus, G, GPa	Poisson's ratio
Carbon fiber (*LU-P*)	250	100	0.25
Epoxy matrix (*ENFB*)	3	1	0.35